Compact Tunable Light Source Based on Nonlinear Optics
Topic Number AF94-011: Contract Number F49620-94-C-0041
Final Report: Phase I SBIR

Focused Research, Inc.
1275 Reamwood Ave.
Sunnyvale, CA 94089
January 15, 1995

Executive Summary

Overview

We are pleased to report that the Phase I SBIR project has succeeded in demonstrating the feasibility of a compact tunable blue light source based on an external cavity diode laser and second harmonic generation in a periodically poled lithium niobate waveguide. A breadboard prototype with a footprint measuring 10" x 6" was assembled and tested and is shown below in Figure 1. Tunable operation using the temperature of the nonlinear waveguide has been demonstrated in three different modes: 1) setting the waveguide temperature to the optimum for a specific desired output wavelength using a look-up table, 2) continuous tuning over 2 nm using optical servo control of the waveguide temperature and 3) rapid tuning over 0.3 nm using the finite phasematching bandwidth of the waveguide at fixed temperature. A spectrum of Tellerium vapor was obtained in this last mode to verify the utility of the device for spectroscopy and process control applications.

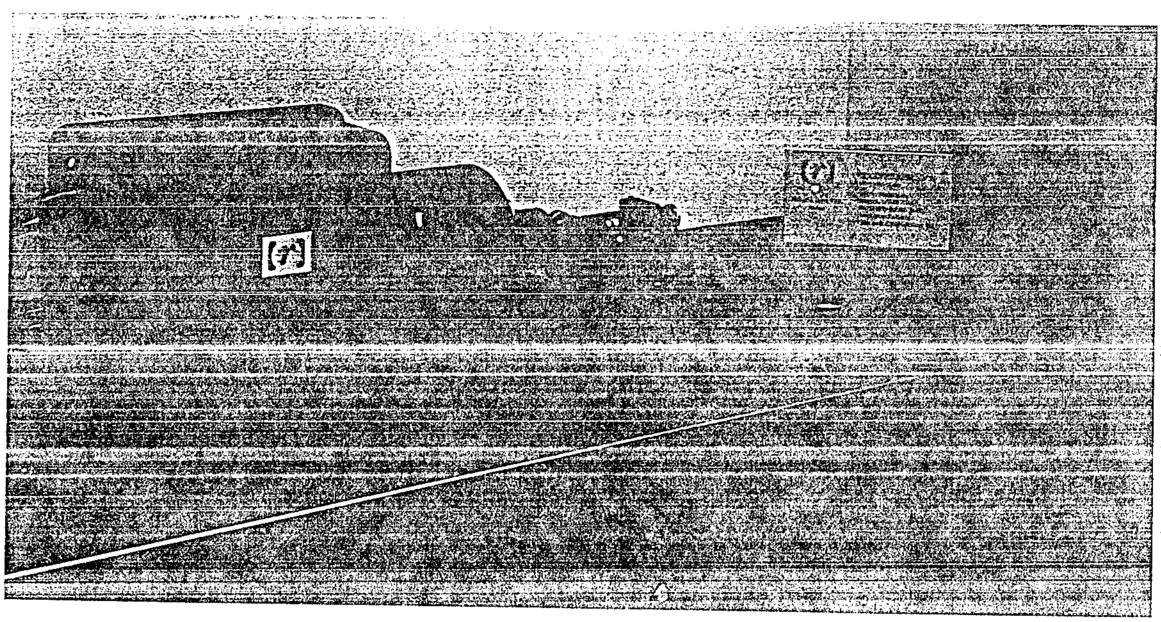

Figure 1. The bread-board blue light prototype in operation

To achieve these results, innovations were necessary in: 1) External cavity diode laser (ECDL) design and construction, 2) waveguide frequency doubler fabrication, 3) compact optical isolator and coupling optics design, 4) opto-mechanical integration of the waveguide stage and coupling optics and 5) dynamic servo control of the waveguide position and temperature. Focused Research adapted and extended previously reported developments in quasi-phasematched waveguide second harmonic generation and leveraged the unique knowledge base of New Focus, Inc - our parent company - in electronics, diode lasers and mechanical actuators. We believe we are well-positioned to pursue this technology further towards reliable sources of tunable blue and near-ultraviolet light for technical and military applications.

The prototype device has proved stable in operation for more than 200 hours. Blue light is obtained as soon as the laser is turned on after shut-down, and the output power remains stable through a typical day of experimentation when the temperature servo is activated. Output powers were in the range of 0.1 to 0.2 mW, below the milliwatt target levels due to the unavailability of a fully-optimized quasi-phasematched lithium niobate second harmonic generation devices. Developing the processing resources needed to manufacture such devices was beyond the scope of this Phase I program; however, SHG waveguide devices with the required performance have been reported in the literature. The feasibility of a **tunable**, single longitudinal mode, blue light source based on nonlinear optics has been demonstrated, and Focused Research is well-positioned to proceed with Phase II development efforts.

The development and feasibility status of the essential system components and system integration efforts are summarized below and described in detail in the Technical Appendix.

1) External cavity diode laser (ECDL) pump source

The fully packaged external cavity diode laser (ECDL) developed under Phase 1 support operated in a single longitudinal mode and tuned continuously from 955 nm to 985 nm. Tuning between 940 and 1040 nm was observed, but with reduced spectral purity. Output powers of over 50 mW were observed around 980 nm with 150 mA of injection current. The external cavity components were designed to allow simultaneous high output power and spectral purity. The packaged laser head is 6"x4"x3", with the essential optical components comprising less than 1/4 of the volume. We believe this is the first single mode strained InGaAs quantum well ECDL in this wavelength range. The laser has been operated for over 200 hrs at the 50 mW output power, indicating a stable antireflection coating technology. The spectral, tuning, and power output properties of the laser were investigated in detail.

2) Waveguide Frequency Doubler

A set of $LiNbO_3$ waveguide QPM-SHG devices employing titanium diffusion for domain reversal and annealed proton exchange for waveguide definition were fabricated. Single longitudinal mode, diode pumped conversion efficiencies between 70 - 80 %/W were observed at output wavelengths near 480 nm. Second harmonic output powers exceeding 0.15 mW were observed with diode laser pumping with

approximately 15 mW coupled into the waveguide. Stable blue output powers exceeding 0.8 mW were observed when the SHG device was pumped with 35 mW from a titanium-sapphire laser. Anti-reflection coatings on the input and output faces of the SHG chip would increase blue output power by nearly 50 %. Nearly ideal phase-matching behavior was observed from the 1 cm long SHG waveguides.. Diode pumped waveguide QPM-SHG was lifetime tested over 200 hrs with no appreciable reduction in SHG conversion efficiency. Tuning was investigated both by varying the temperature of the chip with the light coupled into a single waveguide and by using waveguides with either different QPM gratings or different widths. The total demonstrated tuning range in a single waveguide was nearly 50 Å; use of multiple waveguide allowed tuning over 50 nm, exceeding the tuning range of the ECDL.

3) Coupling Optics and Isolator

The output beam of the pump laser could be coupled into the APE-$LiNbO_3$ waveguides with a mode-overlap efficiency exceeding 50% with a single-element aspherical lens and correct orientation of the laser and waveguide device. Rather than endeavor complex optical transformations a stable mechanical mount was built to facilitate this orientation. A compact 5 mm aperture terbium gallium garnet (TGG) Faraday rotation isolator employing permanent boron-iron-cobalt magnets was constructed and equipped with polarizers and a waveplate to produce the necessary polarization. However, the waveguide doubler chip was not antireflection coated, and the coatings on polarizers and waveplate were not optimal. Thus the maximum coupling efficiency achieved was roughly 30%, or a power in the waveguide of 15 mW. Proper anti-reflection coatings will raise the coupled power to above 25 mW, sufficient for generating milliwatt levels of blue output power.

4) Mechanical Integration

The key opto-mechanical integration challenge in this project was to couple the free-space output mode of the pump laser into a 2 μm x 4 μm mode of a waveguide with high efficiency, while allowing the system to index from one waveguide on the chip to another. In addition, the system had to be insensitive to temperature variation and environmental vibration. A robust waveguide stage with coupling lenses integrated into the basic support structure was designed and fabricated. A thermoelectrically temperature controlled mounting cell for the waveguide chip was also built with a design which cancels expected thermal expansion and maintaines temperature uniformity within the chip to less than 0.5 °C. The position of the doubler chip could be indexed in two dimensions by piezoelectrically driven micrometer screws, ultimately under computer control. This system proved remarkably stable, maintaining near-optimal coupling once aligned and indexing properly under electronic control. The major mechanical elements of the system (laser, isolator and waveguide stage) were mounted on a single bread-board, pending the design of a shock-isolation system. This system was transported to several local area research laboratories for additional testing and maintained the performance levels described above without any modification.

5) Control Electronics

An electronic temperature control system for the waveguide SHG device capable of operating in two regimes was constructed and tested. In the temperature-set regime, a sensor measured the deviation of the waveguide temperature from a computer-defined set-point, and controlled the thermoelectric element on the waveguide cell to minimize the deviation. In this regime, the phasematching peak could be set to the laser wavelength, as measured by a wavelength readout sensor integrated in the laser head. In the optical feedback regime, the waveguide temperature was locked to the maximum of the second harmonic efficiency curve, even as the laser wavelength was changing. The details behind this method, described in the Technical Appendix, are in the process of being patented. The system operated as expected in both regimes, with a characteristic time constant of roughly 1 second. The output wavelength could be scanned over 20 Å at a rate of 100 MHz/second without losing servo lock or unacceptable blue output power variations.

6) System integration and testing

The breadboard prototype shown in Figure 1 was assembled, equipped with the necessary control electronics and extensively tested, both at Focused Research and at Stanford University. The system performance proved excellent, with only minor unexpected vibration and shock sensitivities being revealed. The output beam was used in realistic scientific applications, and we used this blue source to survey the optical absorption of Te_2 vapor, which is used as a wavelength reference in laser experiments. More than 200 hours of operation have been accumulated without observed degradation of any element of the system.

7) Issues for Phase II

The current bread-board system forms the basis for the design of a product line of compact tunable lasers in the 390-490 nm wavelength regime. However, some issues need to be resolved in a Phase II development effort before manufacturing can begin. The top priority is to secure a reliable source of high efficiency periodically poled waveguide second harmonic generation chips. The specialized and challenging requirements of our tunable laser requires that those devices be manufactured under the control of Focused Research, Inc, rather than at another company or at a university user facility. The waveguide cell and alignment stage will have to be re-designed to accomodate the new doubler chip and facilitate assembly and alignment. The electronic control systems will have to be refined and integrated in a user-friendly package. Some refinements will undoubtedly be required for reliable operation in the field. Finally, computer software to operate the system in a variety of user-defined modes will have to be written and de-bugged.

8) Conclusion

The Phase I program to demonstrate the feasibility of a compact tunable source of blue radiation based on nonlinear optics and extended cavity semiconductor diode lasers has been completed successfully. A bread-board system

has generated more than 0.15 mW of light tunable for ± 10 nm around 473 nm. Higher blue output powers will be obtained once the proven periodically-poled lithium niobate technology has been transferred completely to Focused Research, Inc. The system performed excellently in all respects, confirming the theoretical expectations. A simple new method of locking the wavelength of the maximum harmonic generation efficiency to a tunable laser wavelength was invented and is in the process of being patented. The breadboard system was used successfully in laser spectroscopy, confirming its value as a laboratory tool. Focused Research, Inc. is well-positioned to proceed with Phase II development efforts. We anticipate productization of a tunable blue light source is possible within 2 years with appropriate support.

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Technical Appendix

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demonstrated, and Focused Research is well-positioned to proceed with Phase II development efforts.

The development and feasibility status of the essential system components and system integration efforts are described below

1) Laser development

A special high-power extended cavity diode laser (ECDL) pump source for second harmonic generation near 480 nm was constructed. The fully packaged external cavity laser operated in a single longitudinal mode and tunes continuously from 955 nm to 985 nm. To achieve this performance, we designed a special anti-reflection coating to suppress the self-lasing of the GaAs-InGaAs gain chip. The reflectivity vs. wavelength is shown in Figure 1. We achieved 10^{-3} reflectivity at 976 nm, sufficient for continuously tunable external laser cavity operation.

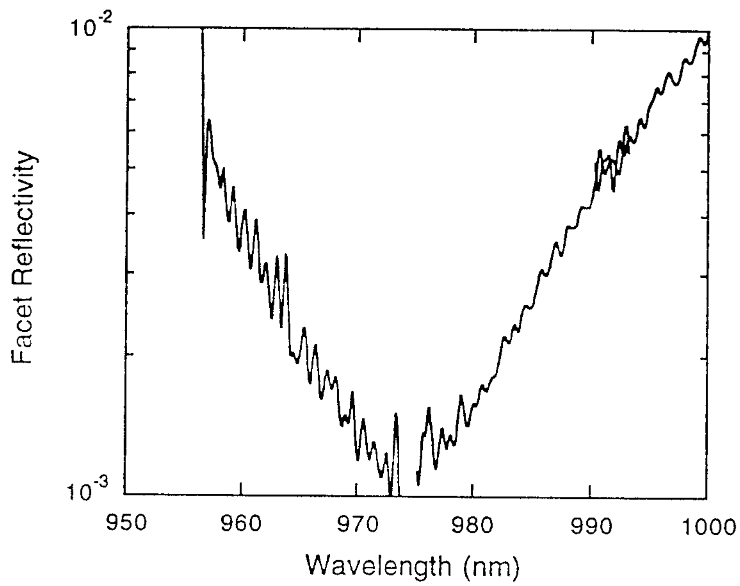

Figure 1. Measured residual reflectivity after AR coating. This laser operates in a single longitudinal mode with external cavity feedback. The coating does not degrade.

The external cavity was designed to faciliate both high output and continuous tuning. In particular, the intracavity diffraction grating was designed to have high output coupling, different from other, low gain ECDL's with lower output powers. When the above gain element was incorporated into the external cavity, output powers exceeding 50 mW were observed at the maximum allowable injection current of 150 mA. Continuous tuning between 955 nm to 985 nm was observed, and tuning from 940 and 1040 nm was observed with reduced spectral purity. Figures 2a and 2b illustrate these performance levels. The laser has been operated for over 200 hrs at the 50 mW output power, indicating a stable antireflection coating technology. The spectral, tuning, and power output properties of the laser were investigated in detail.

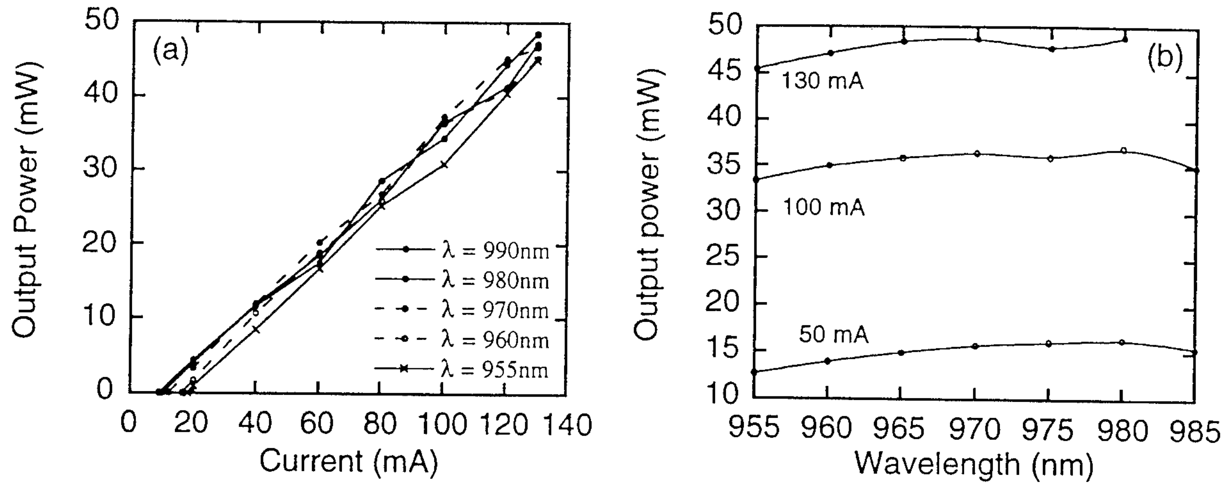

Figure 2. a) Output power vs. injection current at different wavelengths. At the maximum allowable injection current of 150 mA, output powers exceeding 50 mW were observed. b) Output power vs. wavelength at different injection current levels, showing smooth performance over the expected range of operation. All measurements were performed with the laser operating in a single longitudinal mode.

A piezoelectric actuator was incorporated into the laser to allow fine frequency control, allowing up to 3 Å deviations with a 2 KHz bandwidth. Figure 3 shows the laser wavelength vs. piezo voltage. This actuator allows continuous tuning and fine frequency adjust, necessary for a rane of applications including locking the ECDL to absorption lines or other optical cavities. This actuator was used for some of the laser locking and Tellerium spectroscopy experiments described below.

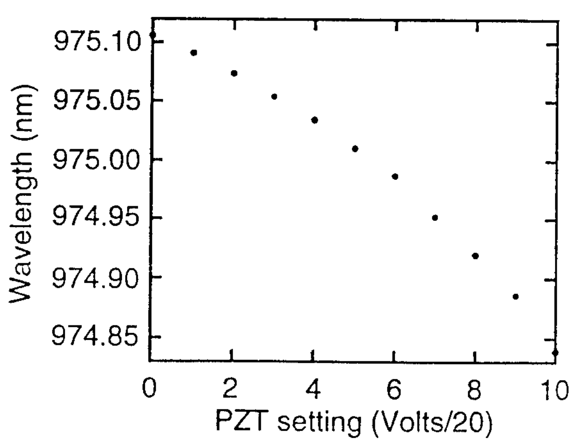

Figure 3. Laser wavelength vs. piezo voltage. This actuator provides fine frequency control over a 0.25 nm range with a 2 KHz bandwidth, suitable fast tuning in addition to lockng the ECDL to absorption lines or other optical cavities.

2) $LiNbO_3$ waveguide QPM-SHG development

2.1) General performance

Periodically poled $LiNbO_3$ waveguide doublers using the titanium diffusion domain inversion process and annealed proton exchanged waveguides were designed and fabricated. We obtained devices from 2 sources; Focused Research personnal fabricated the devices at a local area microfabrication facility and the Uniphase Corporation fabricated devices for us under an informal joint development effort. The devices phasematched at wavelengths between 950 - 1000 nm, as expected from the design. Figure 4a shows a typical wavelength tuning curve from a device, fabricated by us, that phasematched near the middle of this spectral band. The 1 Å bandwidth is in good agreement with the theoretical predictions, shown as the solid line, indicating phasematching over the entire 1 cm device length. Figure 4b is a similar device, fabricated by Uniphase personnel. The conversion efficiencies are nearly identical, ≈ 70 - 80 %/W, and are about a factor of 3 lower than that expected from a fully optimized 1 cm long device. The blue output powers exceeded 0.15 mW with about 15 mW of diode laser infrared pump power exiting the waveguide.

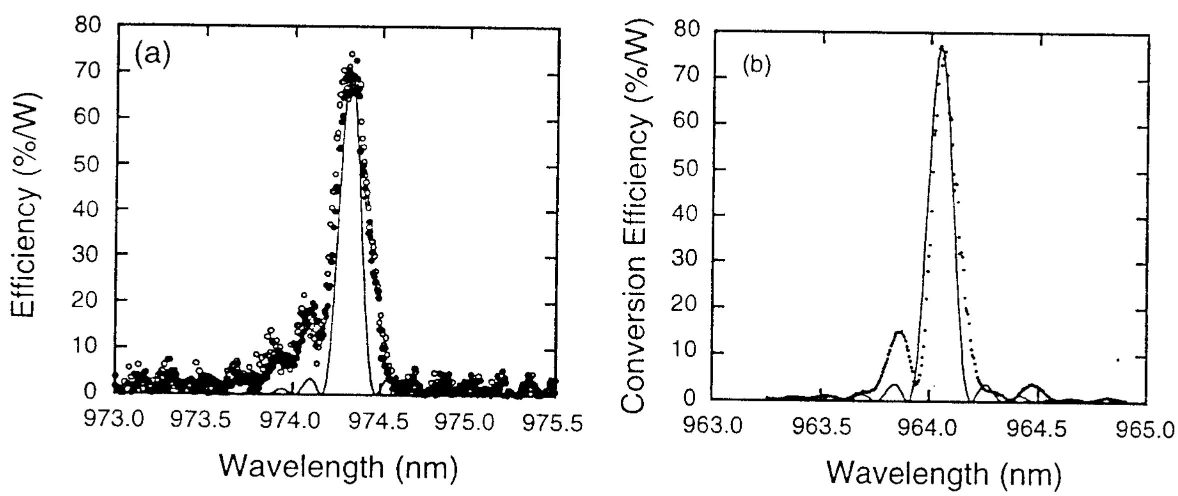

Figure 4. a) Waveguide QPM-SHG tuning curve vs. laser wavelength for a device fabricated by Focused Research personnel. Note the similarity between the experimental and theoretical curves, indicating high device homogeneity. b) Similar result for a $LiNbO_3$ waveguide device fabricated by the Uniphase Corporation under an informal joint agreement. Blue output powers of 0.15 mW were observed in both waveguides using the external cavity diode laser pump source .

2.2) Lifetime and high power testing

A critical aspect of proving feasibility is demonstrating that the blue power output is stable and that the waveguide QPM-SHG device performance doesn't degrade with time. We have performed initial lifetime testing of this diode pumped blue laser system. Figure 5a shows the measured SHG conversion efficiency under diode pumped operation for 8 hrs. The conversion efficiency is essentially constant.

This experiment was performed without closed loop temperature control, and the temperature derivative of the refractive index of $LiNbO_3$ indicates that the small decay is probably due to a monotonic change in the room temperature of roughly 0.5 °C. After the experiment was over, a 0.2 Å change in laser wavelength resulted in the efficiency and blue output power increasing to the initial value, indicating that the laser and waveguide QPM-SHG devices did not degrade. Similar experiments under temperature stabilized operation are ongoing. This is to our kowledge the first lifetime test of a diode pumped waveguide QPM-SHG system. No similar data has appeared in the scientific literature.

Since the ultimate goal of this program is a blue source with milliwatt level output powers, we tested our waveguide QPM-SHG device using a Ti:S laser, a high power infrared pump source. These experiments were perfomed at Stanford University because Focused Research does not have a high power Ti:S laser system. By increasing the pump power in the waveguide to tabout 35 mW, we observed an increase in the blue output power to nearly 0.8 mW. Figure 5b shows the blue output power at the 0.8 mW level vs. time using this high power pump source. This data shows that even at high pump powers, the blue output power is stable. This experiment lasted only ≈ 10 minutes because of pump laser amplitude and wavelength fluctuations. Subsequent experiments showed identical QPM-SHG performance, indicating no device degradation; however, stability of the test system could not be improved past the ≈ 10 minute level. Under Phase 2 support, we would perform high power SHG device testing using a stable laser system.

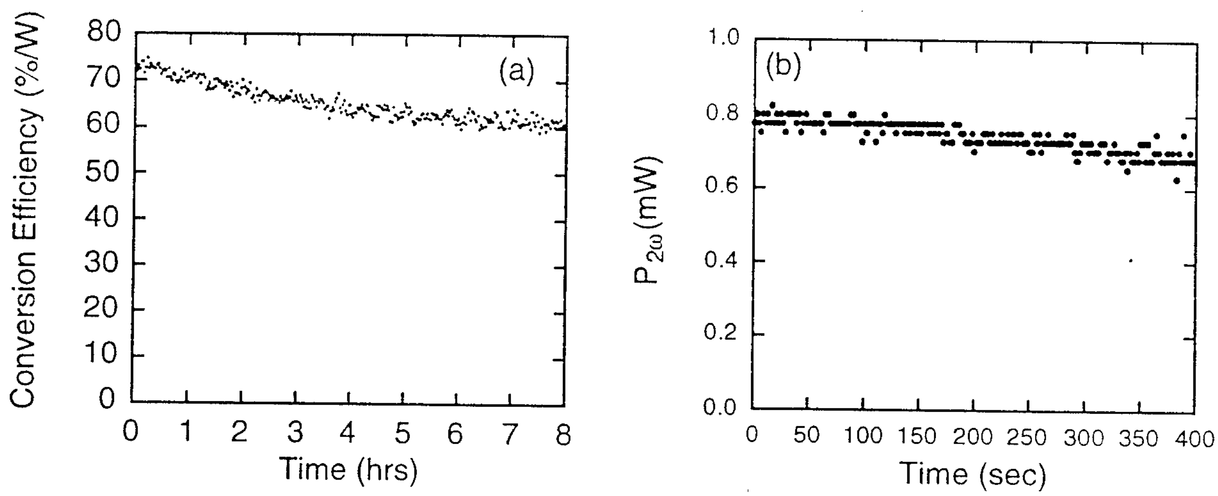

Figure 5. a) Lifetime test of the external cavity laser diode pumped blue light system. The small decay is due to room temperature fluctuations. b) High power blue light generation at the milliwatt level using a Ti:S laser pump source. From one waveguide the blue light output power exceeded 1.2 mW. Pump laser amplitude and frequency fluctuations prevented longer term testing.

In spite of many hours of operation, the available waveguides have shown no evidence of fatigue or degradation. Other researchers have also reported long term stability of similar devices at mW output power levels. Thus, we believe our initial concern about photorefractive index damage, etc., was over-stated, and the device lifetimes are sufficient for continued development efforts.

2.3) Tuning mechanisms

In order to generate tunable blue light, some technique is necessary to circumvent the limited wavelength and temperature acceptance bandwidths for waveguide SHG. The available tuning mechanisms are

1) Temperature
2) Multiple waveguides with different quasi-phasematching gratings
3) Multiple waveguides with different waveguide widths
4) Perturbed QPM gratings

For QPM-SHG of 976 nm radiation, the wavelength and temperature acceptance bandwidth coefficients are approximately 1.4 Å•cm and 2.2 °C•cm. For 1 cm long devices, the FWHM bandwidth will be about 1.4 Å and 2.2 °C. The various tuning mechanisms are each discussed below

Temperature can provide tuning over several nm using a single waveguide. Using a mount designed for simultaneous high thermal uniformity, low thermal mass, and zero thermal expansion, we achieved tuning over 40 Å by varying the waveguide temperature using a simple, thermoelectric cooler. Figure 6a shows the measured wavelength tuning curves at 20 °C and 50 °C. The lower peak efficiency and broadening of the tuning curve at high temperature is due to axial thermal gradients of about 0.5 °C caused by poor thermal contact between the waveguide SHG device and the mount, which will be corrected in subsequent assembly procedures. Figure 6b shows the measured wavelength of peak efficiency vs. temperature, illustrating a tuning range of 40 Å. This information would allow the SHG temperature controller to maximize the efficiency for each given wavelength using a look-up table. The solid line is calculated from the bulk $LiNbO_3$ refractive index data and indicates that the proton doped waveguide material has a temperature dependence different from $LiNbO_3$.

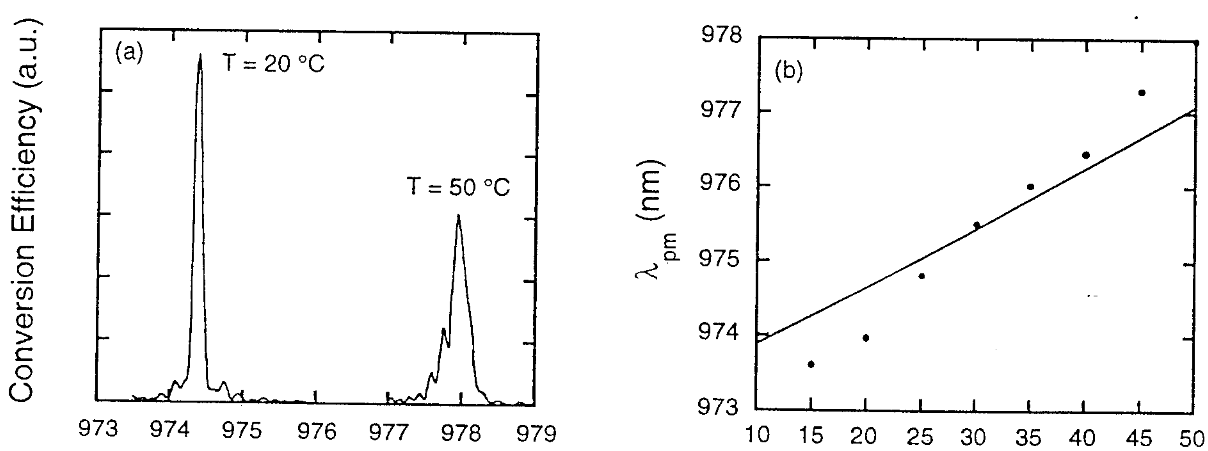

Figure 6. a) wavelength tuning curves at two differetn temperatures. The reduction in efficiency at 50 °C is caused by axial gradient of < 0.5 °C due to use of an inappropriate thermal epoxy. b) Wavelength of peak efficiency vs. temperature. Tuning over 40 Å can be acieved in a single waveguide using temperature.

Multiple waveguides will be necessary for broad tuning over a range exceeding about 50 Å. Figure 7a shows phasematching wavelength vs. QPM period for an array of devices on a single sample. This tuning range of 25 nm in the blue, or 50 nm in the infrared, exceeds the tuning range of the external cavity diode laser.. Figure 7b shows phasematching wavelength vs. waveguide width for an array of devices on another sample. Tuning using the variation with width is less practical than the variation with QPM period since the modal properties of the waveguide vary with width. However, this effcect is a useful diagnostic of material processing, since calculation of phasematching wavelength vs. width can be compared with theory, as shown by the curve in Figure 7b.

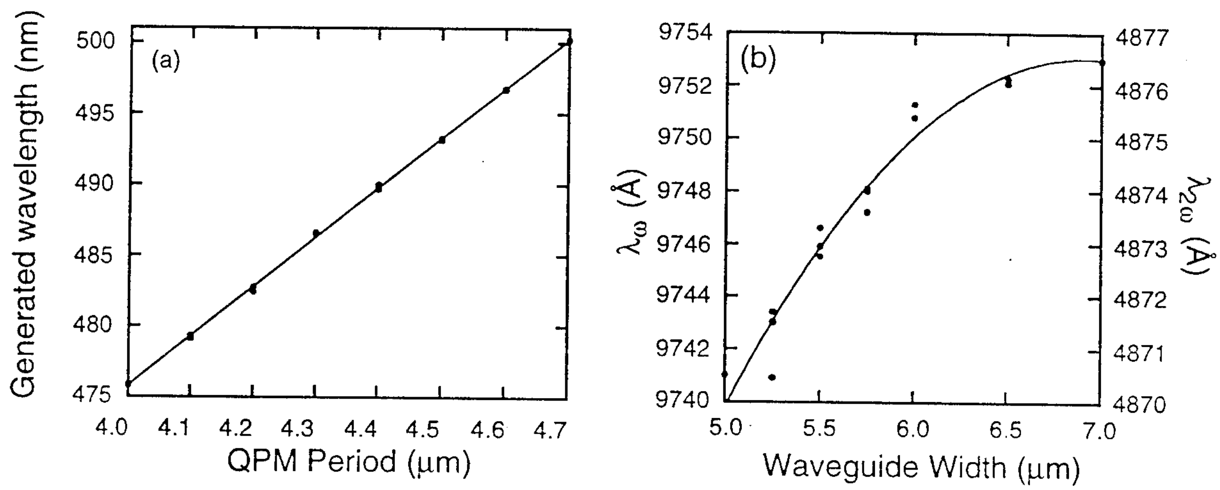

Figure 7. a) Variation of phasematching wavelength with QPM period. Nearly infinet tuning is possibel using this approach. b) Variation of phasematching wavelength with waveguide width. This tuning approachis not as practical as the one shown in Figure 7a; however, the variation with width is an important diagnostic of device efficiency and performance.

Widely tunable sources will use temperature control in conjunction with additional tuning techniques, such as selecting waveguides with different center wavelengths. In Phase II, we will design and fabricate arrays of waveguides with peak phasematching efficiencies varying in 2 nm steps. Thus any given wavelength will be accessible in three different adjacent waveguides at three different temperatures. This will result in a device with truly continuous tuning over a 50 Å bandwidth at any center wavelength, essential for spectroscopy and process control applications.

2.4) Approaches for increasing blue output powers

The titanium diffusion process does not produce the rectangular domain profiles that appear in calculations of ideal QPM performance. Rather, the domains are more triangular as shown below in Figure 8. The reduction in conversion efficiency was expected to be about a factor of 3-4. However, our initial waveguides showed a greater efficiency reduction, and microscopy analysis of the domain

gratings revealed shallower angles for the domain triangles than obtained previously. The domain apex angle and the location of the boundary between inverted and non-inverted domains in the waveguide depend on the thermal processing for titanium diffusion. We expect substantial improvements in conversion efficiency once the thermal processing conditions have been optimized.

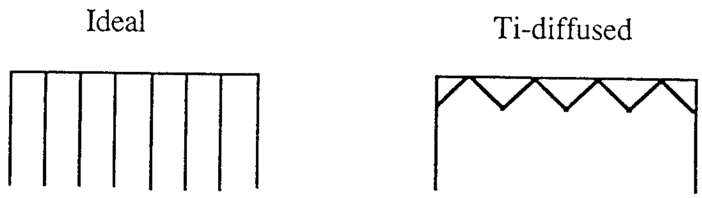

Figure 8. Schematic diagram comparing ideal and titanium diffused domain inversion gratings. The domain angle commonly achieved with the "standard" diffusion process is between 90 ° and 120 °.

Recent developments at Stanford University and at IBM using direct application of high voltage pulsed electric fields have resulted in periodically poled $LiNbO_3$ and KTP with a nearly ideal domain inversion structure. Devices have demontrated normalized efficiencies exceeding 1000 %/Wcm^2, and promise reduced sensitivity to processing fluctuations. We are monitoring these developments and will substitute electric field poled $LiNbO_3$ for the titanium diffused material if and when the electric field poling process is demonstrated to be reproducible and amenable to manufacturing processes.

3) Isolator and Coupler Design

A Faraday rotation optical isolator emplying a 20 mm length of terbium gallium garnet and boron-iron cobalt magnets was designed, assembled, tested and incorporated in the system. Including the necessary Glan-Thompson polarizers, it had an overall length of 8 cm. The measured isolation was 33 dB. Equipped with a zero-order half wave plate the isolator was capable of producing a clean wavefront with the proper polarization to launch into the QPM waveguide while protecting the laser from feedback.

The external cavity semiconductor diode laser produced a collimated output beam with an elliptical Gaussian mode profile. The major axis of the ellipse was 5.7 mm and the minor axis was 1.9 mm. When focused by a diffraction limited lens with a 6 mm focal length this beam matched the mode of the QPM waveguides with a theoretical modal overlap factor of 60% when the major axis was oriented perpendicular to the surface of the waveguide. In ordinary operation, the major axis of the laser is horizontal, as is the surface of the waveguide chip. Consequently, we built a stable mount for the laser which permitted it to operate on its side, making the major axis vertical. Using the isolator and half wave plate to properly orient the polarization, we achieved over 50 % modal coupling into the waveguide without complex anamorphic optics.

Poor anti-reflection coatings on the polarizers, along with the 5 mm diameter isolator, resulted in only about 35 mW incident on the waveguide endface. The

uncoated waveguide endface results in a 14 % optical loss, and so only 15 mW of 980 nm radiation was coupled into the waveguide. We estimate that improving the coatings and running the laser at maxium rated power would result in 22 mW coupled into the waveguide. With a nominal 200%/W conversion efficiency, this would produce 1 mW of radiation tunable between 470 - 490 nm.

4) Mechanical Integration

The most delicate facet of a system which generates blue light by second harmonic generation in different waveguide is coupling the free-space laser beam - which is typically several millimeters in diameter - into the proper micron-scale guide. Elaborate multi-axis translation stages with differential actuators are typically used for laboratory experiments. To move towards a practical system, we designed an integrated stage with electronically controlled actuators to translate the SHG chip. The coupling lenses were mounted directly on the frame of the translation stage, increasing mechanical rigidity. Figure 9 shows the Cad-Key™ design of the stage, with piezoelectric actuators, the thermoelectric cooler, and the heat sink.

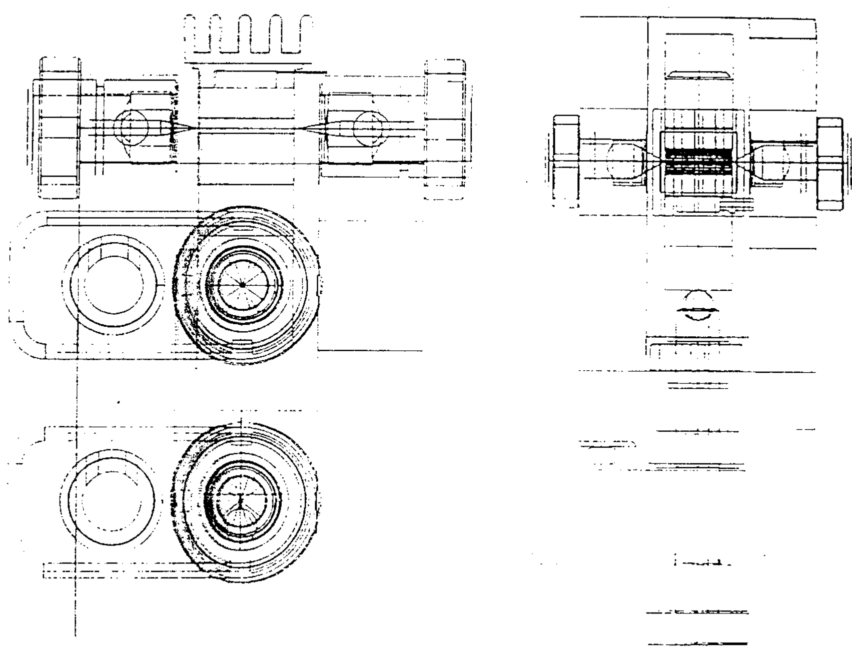

Figure 9. Prototype waveguide mounting stage with electronic control.

Temperature tuning the peak phasematching wavelength requires a mounting cell for the waveguide chip to be compensated for the thermal expansion of the lithium niobate and the cell material. We designed a cell made of copper and aluminum which had the proper temperature stability and compnesated thermal expansion, and could be heated or cooled by a thermoelectric cooler. A thermal sensor integrated in the cell allowed closed-loop control of the chip temperature with accuracy better than 0.1°C.

The prototype mounting cell could be controlled at temperatures between 15°C and 45°C, but poor thermal contact between the chip and the mount led to unacceptable gradients (and a reduction in doubling efficiency, as shown in Figure

6a) when the chip was held more than 20°C away from ambient. The first generation prototype had a thermal time constant of >1 sec, which made dynamic control difficult. An improved cell will be necessary in Phase II.

Automatic maximization of the waveguide coupling efficiency requires two error signals, one for the vertical and one for the horizontal direction. The first prototype could only generate such an error signal by stepping the main actuators under computer control. While these actuators have a resolution of 20 nm, hysteresis and other effects makes automatic optimization difficult. A second generation waveguide mount would have piezo-electric translators to dither the position of the input lens, allowing continuous servo optimization of the coupling using lock-in techniques.

The laser, isolator and waveguide stage must be rigidly connected to one another by a mechanical frame. In the prototype, this was a simple plate of aluminum, which was found suitable for operation in a vibration-free environment. When properly aligned, the system was remarkably insensitive to environmental parameters. A more rigid frame - fabricated out of heavy gauge aluminum angle with vibration and shock absorbing material - will be necessary in Phase II.

5) Control Electronics

A Proportional/Integral (PI) temperature control circuit was adapted to maintain the temperature of the waveguide chip cell to within 0.1°C of the nominal setpoint. The temperature controller circuit allow for manual, single set point control or for automatic, analog input control. The temperature required for doubling a particular wavelength is given in Figure 6b. The Phase II system will allow direct computer control of the setpoint.

Many applications required a more sophisticated control approach. An elegant method to control is to use an optically generated bipolar error signal. It is possible to use an applied electric field to modulate the phasematching condition of the waveguide using the electro-optic effect. This imparts a AC component on the blue light generation, with a phase relative to the driving voltage that depends on the sign of the phase mismatch. Phase sensitive detection can provide a bipolar error signal. The modulation can be very small so that amplitude modulation is irrelevant and at a low frequency of 100- 1000 Hz, so sideband generation can be ignored. Modulation frequency can be easily varied with a VCO. In an **ideal** QPM-SHG device this effect will be zero, since the sign of the electro-optic coefficient varies just as does the sign of the nonlinear optical coefficient. Thus this technique suffers from having to develop an interdigital electrode structure with the sign of the applied field varying every 1/2 period. Since required QPM periods are roughly 4 μm, this interdigitated electrode structure would require ≈ 1 μm alignment to the QPM grating, a difficult lithography process.

However, QPM structures are not ideal. A small asymmetry in the QPM grating duty cycle will have a negligible effect on SHG conversion efficiency, but will result in some electro-optic modulation using a simple *planar* electrode. This is very simple to implement. Using the existing blue laser system, a simple planar electrode structure built around the SHG device, and a low voltage signal generator, we implemented this modulation technique. Figure 10 shows the blue light output power and the observed error signal measured using phase sensitive detection vs. laser wavelength. Modulation voltages of several volts resulted in mV level error

signals, and making sophisticated signal processing unnecessary and rendering noise irrelevant. As expected, the error signal looks like the derivative of the blue output power.

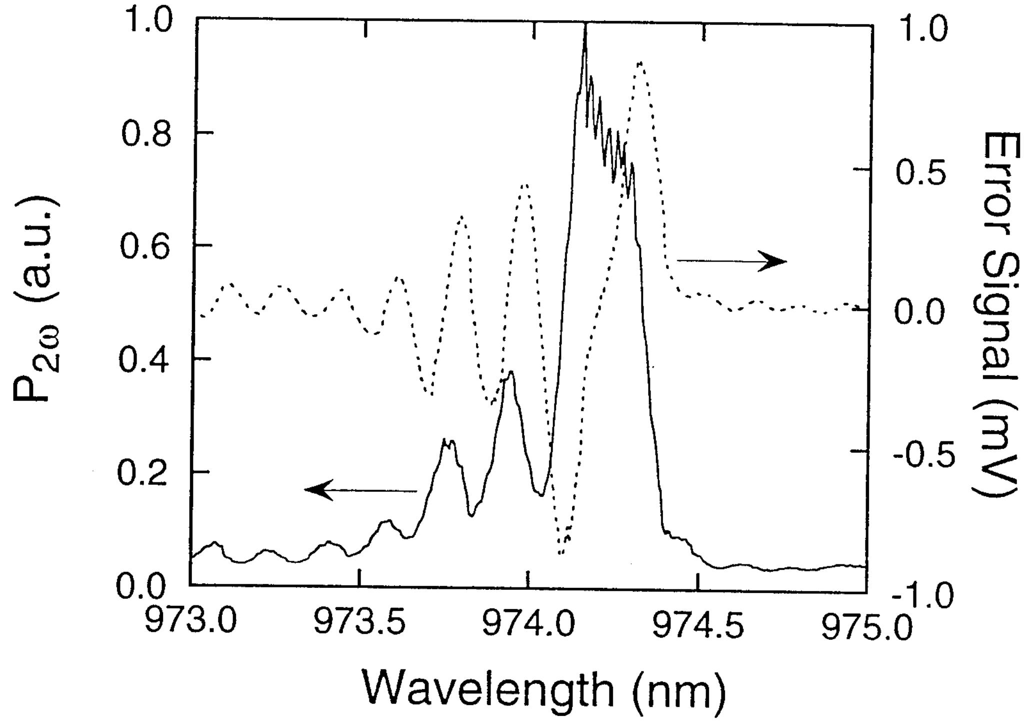

Figure 10. SHG efficiency and electro-optical phase matching error signal. The small dither imparted on the phasematching curve along with phase sensitive detection results in an error signal that is the derivative of the phasematching curve. Note the. enormous capture range (≈ 1 Å, or 30 GHz) available for closed loop applications.

The electro-optical error signal was used to control the temperature of the doubling chip using a P.I.D. controller and a modified drive circuit for the Peltier effect element. The servo drove the error signal to zero reliably at each wavelength, insuring that the the temperature of the waveguide was set at the true maximum of the phase matching curve. The electro-optical servo system could also be used to set the wavelength of the laser to the maximum of the efficiency curve, allowing the maximum efficiency to be generated even when the chip is rapidly heated or cooled. In addition, when the laser was scanned at a rate below 6 GHz/min, the servo system locked the chip temperature and wavelength together, permitting scanned operation. This will be discussed further under Prototype testing.

The capture range for this error signal is roughly equal to the SHG bandwidth of ≈ 1 Å, enormous by control standards. The large capture range of the error signal greatly reduces the accuracy requirements for the look up table and wavelength sensors since they only need to provide control to within the capture range of the eletro-optically induced error signal, rather than providing control to the phasematching peak. Once the temperature is set within the cature zone, the opto-electronic servo automatically maximizes efficiency. Furthermore, using this control technique temperature fluctuation and system drifts can be easily

accommodated. Focused Research has applied for a patent on this control technique as applied to QPM-SHG.

The parameters of the necessary control system have been defined, but a final electronic design awaits charactrization of a second-generation chip cell and coupling lens mount. Much of the control is likely to be implemented digitally using a personal computer.

6) Breadboard Prototype tests

The breadboard prototype illustrated in Figure 1 in the Executive Summary was assembled and equipped with control electronics for the waveguide temperature. The electronic actuators for the waveguide position were controlled by a hand-held pad, rather than automatically. The general performance chanracteristics of this device were as follows

Size: 10" x 6" x 6"
Weight: 10 lbs
Fundamental power: 50 mW
SHG power: 0.15 mW
Continuous tuning range: 40 Å (1200 GHz)
Overall tuning range: 25 nm (30,000 GHz)
Linewidth < 20 MHz
Beam quality: Diffraction limited ($M^2 \approx 1$)
Lifetime : > 200 hrs

The most critical system parameter turned out to be the relative positions of the waveguide and input coupling lens. This could be optimized manually, and once optimized was stable for hours. The electro-mechanical actuators were capable of translating the waveguide chip to access successive guides, allowing the output wavelength to be stepped by 4 nm at constant temperature. The breadboard prototype system was used to generate most of the data contained in this report.

To evaluate the long term performance of the system, the SHG output power was measured by computer over an eight hour period, but without temperature control. Figure 11 shows a typical result; the 15% decline over eight hours was due to the overnight flucuations in the ambient room temperature and was corrected at the end of the test by a 0.2 Å readjustment of the laser wavelength.

Since the purpose of this project was to demonstrate a compact tunable blue light source, several tests were made of scanned operation. The most challenging of these tests was to scan the laser continuously over 2 nm, or nearly 600 GHz, while maintaining peak harmonic generation efficiency using the opto-electronic servo. The wavelength of the second harmonic output would vary by 1 nm, or 1200 GHz and the temperature of the waveguide would change by about 10 °C. Figure 12 shows a block diagram of the complete system, including the control electronics. For feasibility studies, the signal generator, lock-in amplifier, PID controller, and temperature controller used were discrete electronic components; in a commercial system, they would be integrated into a single controller.

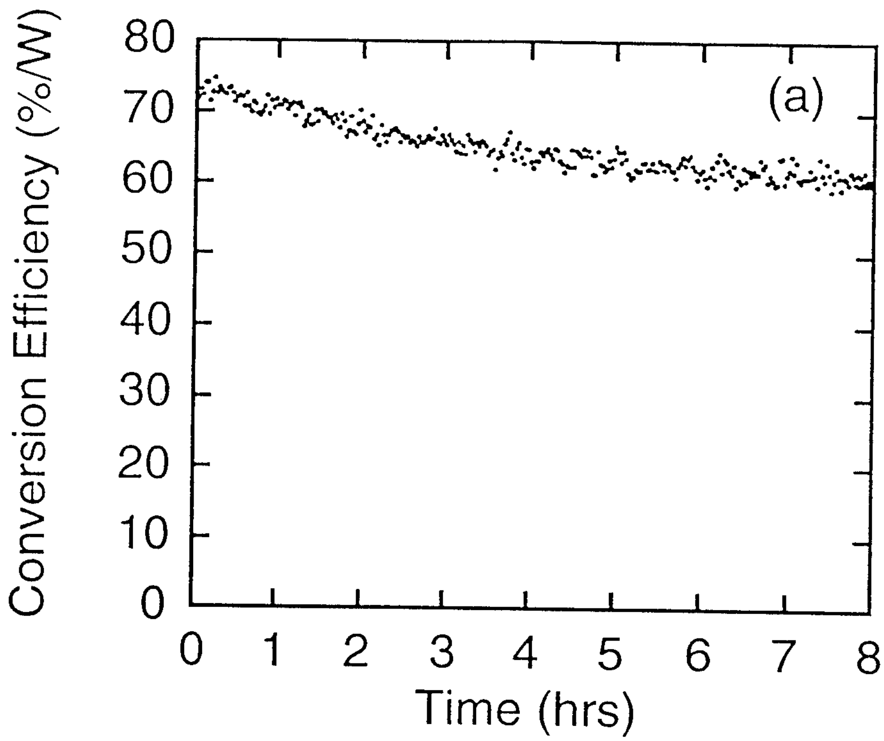

Figure 11. a) Lifetime test of the external cavity laser diode pumped blue light system. The small decay is caused by overnight temperature variations.

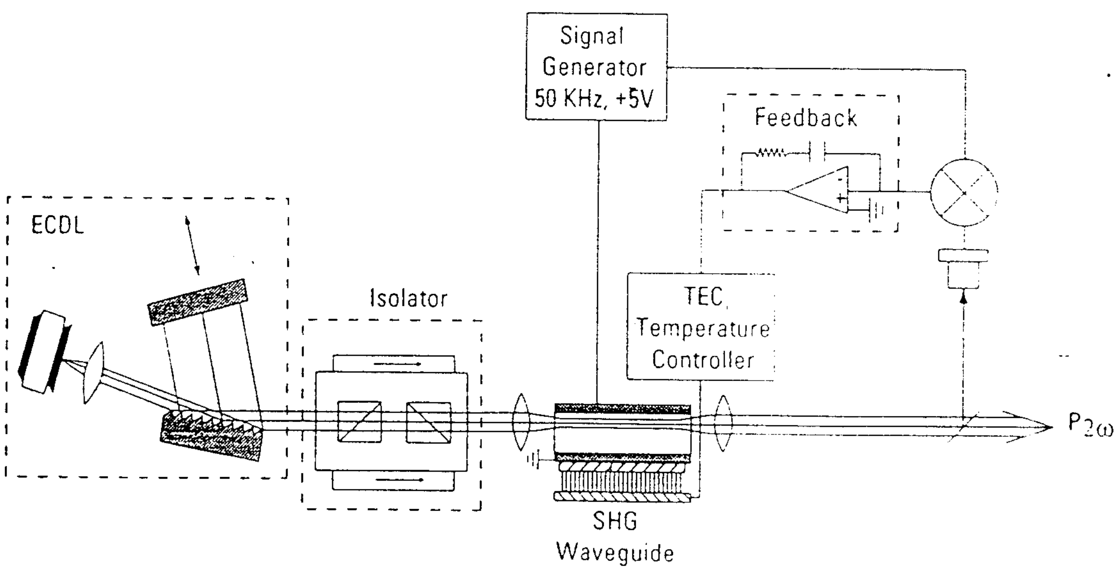

Figure 12. Block diagram of the system used to perform closed loop continuous scanning.

Figure 13 shows the second harmonic output power generated with the servo on (temperature scanning autonomously) and off (temperature fixed). The output oscillations reflect the 30% variations in laser output with wavelength that result from the 0.1% reflectivity of the output facet of the semiconductor diode chip. With better anti-reflection treatment of the facet, this oscillation would be reduced by a factor of 10. Nevertheless, the laser scanned continuously over the wavelength range required and the servo maintained lock in spite of the power variation. The power roll off at high and low wavelength results mostly from temperature gradients forming in the prototype waveguide mounting cell due to poor assembly techniques, easily overcome by using better thermally conductive epoxies. The width of the wavelength scan is over ten times larger than the phasematching peak at constant temperature. and with proper design of the thermal environment the scan range should approach 40 Å. The laser was scanned at 100 MHz/sec, which is close to the maximum scan rate that is useful for high-resolution laser spectroscopy.

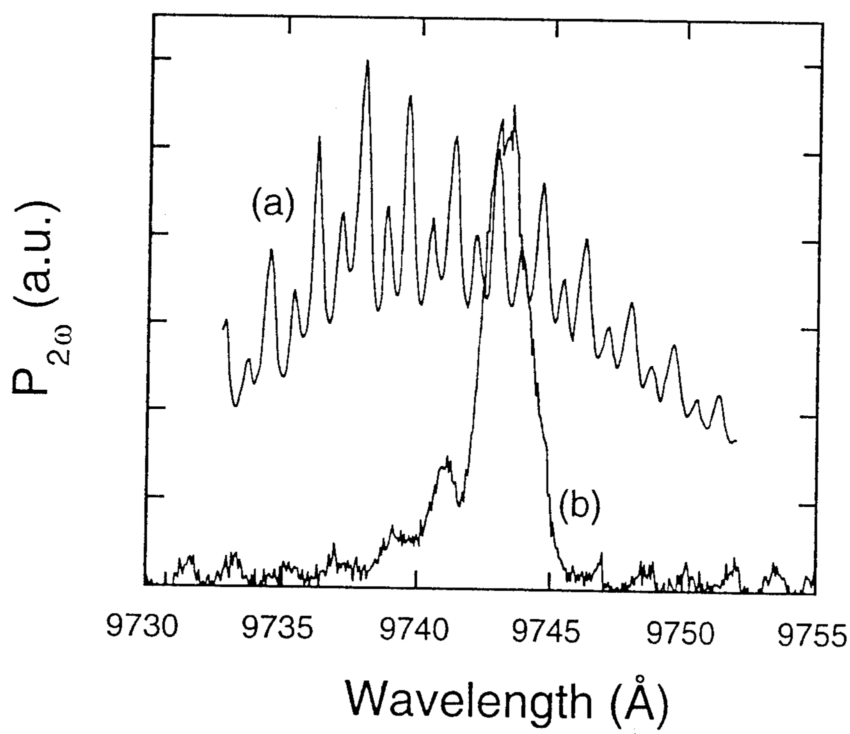

Figure 13. The second harmonic output power as a function of pump laser input wavelength. a) A 2 nm scan under closed loop control with the temperature of the QPM-SHG waveguide controlled by the opto-electronic servo, and b) with the temperature of the QPM-SHG waveguide held fixed.

To prove that the breadboard prototype system could be used in spectroscopy applictions, we scanned the absorption of Tellurium vapor in the region around 473 nm. Te_2 vapor has numerous narrow lines in the 465 nm - 550 nm region, and is widely used as a wavelength reference in laser spectroscopy. However, the vapor pressure of tellurium is low and the absorptions are typically rather weak. To maximize the sensitivity we used a wavelength modulation spectroscopy technique.

We dithered the wavelength of the source laser at 1 kHz, and used differential lock-in detection. Figure 14a shows a digitized oscilloscope trace corresponding to a single scan of 10 GHz across part of the Te_2 absorption band near 488 nm. Three strong absorptions can be seen, with several weaker lines as well. Obtaining similar traces with conventional laser technology would require either an argon-pumped dye laser system operating with relatively unstable stilbene dye or an argon-pumped Ti-sapphire laser and second harmonic generation. Either system would be an order of magnitude larger, require two orders of magnitude more power and cost at least 4 times as much as this prototype.

To verify the resolution of the laser system, the strong isolated peak at the right hand side of Figure 14a was scanned, with computerized data logging. Figure 14b shows the result, which has the expected derivative Gaussian lineshape as detected by the wavelength modulation technique. The laser linewidth of < 10 MHz was not sufficient to produce observable broadening. Wavelength drift over a one hour period was not detectable, indicating excellent absolute wavelength stability.

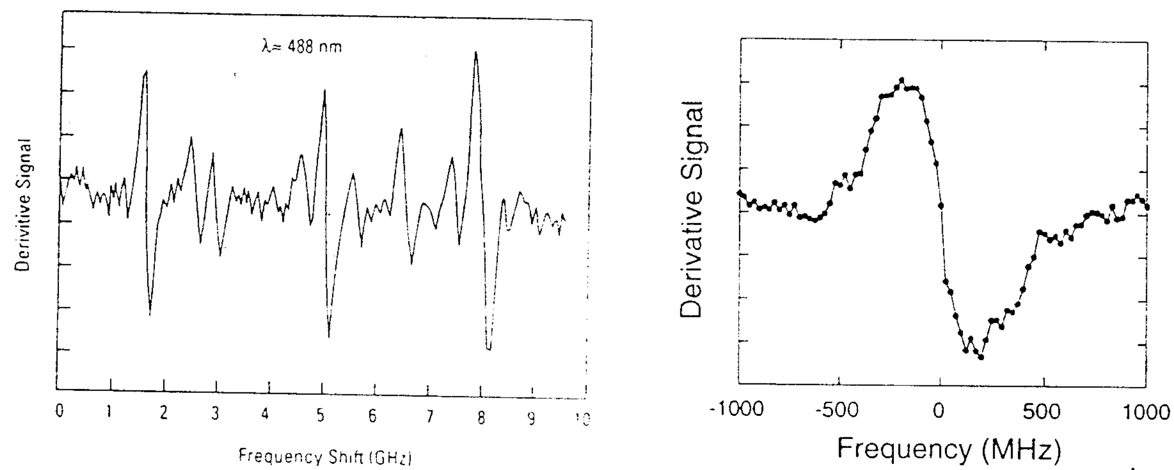

Figure 14. The absorption of Te_2 vapor as resolved by the breadboard prototype light source around 488 nm. a) 10 GHz scan over many absorption lines and b) a high resolution scan of the line on the extreme right of Figure 14a. No line broadening due to source instability or linewidth fluctuations were observed.

While tellurium vapor may be of interest only to physicists, NO_2 also has a structured spectrum in this wavelength range. While more complex than tellurium, the characteristic absorption spectrum can be used to quantify NO_2 concentrations in the environment and in combustion if a convenient and reliable tunable source were available. The device demonstrated here has the potential to fulfill that role.

7) Conclusions

We have demonstrated a compact tunable source of blue light based on extended cavity diode laser technology and second harmonic generation in a lithium niobate quasi-phasematched waveguide. The first bread-board prototype

demonstrated the feasibility of producing milliwatt levels of optical power in the 470-490 nm wavelength range. Various methods of choosing the output wavelength and tuning the source were documented. The source proved to be stable and robust in a laboratory environment. The laser was applied to measuring the spectrum of Te_2 in a wavelength regime where other convenient tunable sources are not available.

Processing of more efficient waveguide doubling chips and development of optimized hardware and software awaits funding of a Phase II program. This technology can be employed for wavelengths between 390 nm and 500 nm using different semiconductor lasers and waveguide designs. The ultimate applications under investigation at Focused Reseach and New Focus involve environmental monitoring and industrial process control.

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13. ABSTRACT (Maximum 200 words)

Periodically Poled waveguides on lithium niobate and other nonlinear materials capable of quasi-phase-matched second harmonic generation have recently achieved conversion efficiencies above 100% per watt. Combined with semiconductor diode lasers, such waveguide devices promise compact sources to blue and green light (390-490 nm) with power above 2 mW today and above 100 mW in the future. An essential prerequisite is a stable pump source, such as the external-cavity diode lasers (ECDL's) produced by New Focus, inc. The second harmonic can be tuned by varying the input wavelength and the temperature of the nonlinear waveguide simultaneously, or designing a broad phase-matching band. In some applications such as holographic data storage and process monitoring, tunable narrowband blue and green light is highly desirable. The ECDL doubler concept provides convenient tunability with little increase in complexity. We propose to combine periodically poled waveguide technology with compact new ECDL designs to achieve a tunable blue/green source in a 4" x 4" x 6" package, which may be reduced to 1" x 1" x 3" - or even smaller - by incorporating micro-optical and micro-mechanical components. The success of this program will facilitate for compact nonlinear optical sources in the 3000-5000 nm range.

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